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Nicholas T. Arndt[1], **C. Michael Lesher**[2,3], **Michel G. Houlé**[2,3,4], **Eric Lewin**[1], **Yannick Lacaze**[1]

[1] LGCA, UMR5025 CNRS, Université Joseph Fourier, Grenoble, France

[2] Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Sudbury, Ontario, Canada

[3] Ottawa-Carleton Geosciences Centre, University of Ottawa, Ottawa, Ontario, Canada

[4] Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario, Canada

Abstract

Although komatiite has been defined as an ultramafic volcanic rock characterised by spinifex texture, there is a growing recognition that similar textures form in high-level dykes and sills. Here we report the results of a petrological and geochemical investigation of a ~5m thick komatiite sill in Dundonald Township, Ontario. This unit forms part of a series of komatiites and komatiitic basalts, some of which clearly intruded unconsolidated sediments. The komatiite sill is differentiated into a spinifex-textured upper part and an olivine cumulate lower part. Features characteristic of the upper sections of lava flows, such as volcanic breccia and a thick glassy chilled margin, are absent and, instead, the upper margin of the sill is marked by a layer of relatively large (1-5 mm) solid, polyhedral olivine grains that grades downwards over a distance of only 2 cm into unusually large, centimetre-sized, skeletal hopper olivine grains. This is underlain by a ~1m thick zone of platy spinifex-textured olivine and coarse complex dendritic spinifex-textured olivine. The texture of the olivine cumulate zone in the overlying unit is uniform right down to the contact and a lower chilled margin, present at the base of all lava flows, is absent. The textures in the sill and the overlying unit are interpreted to indicate that the sill intruded the olivine cumulate zone of the overlying unit. Thermal modelling suggests that soon after intrusion, a narrow interval of the overlying cumulate partially melted and that the liquid in the upper part of the sill became undercooled. The range of olivine morphologies in the spinifex-textured part of the sill were controlled by nucleation and crystallization of olivine in these variably undercooled liquids.

Introduction

A few years after Mike O'Hara finished his work on the Scourie picritic intrusions (O'Hara, 1961), Naldrett and Mason (1968) published one of the first complete petrological descriptions of a komatiite. At that time, about a year before Viljoen and Viljoen's (1969a,b) papers defining komatiite as a new type of volcanic rock, most of the petrological world shared Bowen's doubts about the existence of ultramafic magmas (Bowen, 1956). Naldrett and Mason (1968) presented detailed descriptions of skeletal olivine morphologies in a series of ultramafic units in Dundonald Township, Ontario. Although they recognised that these textures were attributable to very rapid cooling, they hesitated to call the units lavas and instead interpreted them as a series of high-level intrusions.

The komatiites in Dundonald Township were largely neglected in following years as attention turned to better exposed units ~50 km to the east in Munro Township (Pyke *et al.* 1973) and ~5 km to the northeast around the Alexo mine (Barnes *et al.*, 1983; Arndt, 1986). Muir and Comba (1979) studied the Ni-Cu-PGE mineralisation in central Dundonald Township and although they recognized numerous "interflow" breccias containing mixtures of graphitic material, volcanic clasts, and sulfides, they interpreted the units that hosted the mineralisation as extrusive. In 1989, a large area of outcrop in Dundonald Township, immediately north of the komatiite occurrences described by Muir and Comba (1979), was stripped of vegetation during evaluation of the sulfide mineralization by Falconbridge Ltd. Mapping of the stripped outcrops by Davis (1997, 1999) indicated that the "interflow" breccias were peperites and that the thin komatiitic basalts intercalated with them were sills. More detailed mapping has shown that many, perhaps most, of the komatiitic units in the sequence are intrusive (Houlé *et al.*, 2002a,b, 2004a; Cas *et al.* 2003).

The question of whether many other komatiites might be intrusive was brought into the limelight by Grove, de Wit, Parmen, and coworkers (Grove *et al.* 1994, 1997; Parman *et al.* 1996), who suggested that the komatiites in the Barberton greenstone belt in South Africa were emplaced as a series of mid-crustal sills, rather than as lava flows. This question is very important because Barberton is the type area of komatiite, the site where the new type of *volcanic* ultramafic rock was first described by Viljoen and Viljoen (1969b). Grove, de Wit, Parman and co-workers advanced two principal arguments to support their interpretation. First, on the basis of field and petrographic observations, they concluded that the komatiites of the Barberton Belt are discordant and intrusive. Second, they proposed that komatiite magma is hydrous and forms in Archean subduction zones, a possibility previously suggested by Allègre (1982). Because the solubility of water in silicate liquids depends strongly on pressure, a hydrous magma will not reach the surface without degassing and is more likely to intrude into upper crust than to erupt on the surface. Grove *et al.* (1997) suggested that Barberton komatiites formed in this way. Although it has long been clear that *some* komatiitic rocks are intrusive (e.g., Williams, 1979; Pyke, 1982; Davis, 1999; Stone and Stone, 2000; Beresford and Cas, 2001), and that others contained as much as 1-2% H_2O (Stone *et al.* 1997), detailed mapping and petrographic studies by numerous workers in Australia, Brazil, Canada, Finland, South Africa, and Zimbabwe have shown, through the identification of hyaloclastite flow-top breccias and other features indicative of eruption, that most komatiites are extrusive.

An evaluation of komatiite units in which intrusive relationships appear unequivocal indicates that these units invaded sequences of unconsolidated sediments. This is to be expected because unconsolidated sediments are much less dense than komatiitic magma and, for rheological reasons, more difficult for magma to traverse than brittle volcanic rock. However, the question of whether komatiites are capable of intruding other komatiites or mafic volcanic rocks, as suggested by Grove and co-workers for the komatiites in Barberton, remained unanswered.

The purpose of this paper is to provide a detailed field and petrologic description of a ~5m thick komatiite unit at Dundonald Beach (Figs. 1-3) and to present arguments for an intrusive origin. We compare the probable features of intrusive komatiites with those of well-documented komatiite flows in Canada, Australia, and southern Africa, and show that apart from the upper contact, which provides convincing evidence of an intrusive origin, there is little to distinguish the sill from a typical spinifex-textured komatiite flow. We then demonstrate, using mineralogical and textural evidence, that the magma that formed the sill contained very little water, and that an intrusive setting by no means indicates that the parent komatiite was hydrous.

Methodology

The entire stripped outcrop area of Dundonald Beach (Fig. 2) was mapped at 1:250 scale between 2000 and 2003 as part of M.G. Houlé's PhD dissertation at Laurentian University and the University of Ottawa (Canada) and as part of collaborative projects with Université de Grenoble (France) and Monash University (Australia). In this particular study we mapped the two westernmost exposures of the komatiite sill at scales of 1:50 (Fig. 3). Samples from the outcrop shown in Figure 3 were slabbed and the polished surfaces were scanned to produce the images reproduced in Figure 5. Thin sections of the samples were imaged (Figs. 6, 7) and studied in detail. With the exception of irregular patches in the lower olivine cumulate zones, secondary minerals have pseudomorphically replaced all of the olivine and much of the pyroxene. Although this alteration precludes detailed study of primary mineral compositions within the unit, it has accentuated the contrast between dark serpentinized olivine and paler matrix, highlighting the relict igneous textures. Variations in the sizes and orientations of olivine crystals in the upper part of the unit were documented by tracing their long dimensions by hand on images of outcrops, scanned slabs, or thin sections, then analyzing the results using MATLAB®. The results are shown in Figure 8.

Geological setting

Dundonald Township is located ~40 km northeast of the city of Timmins in northern Ontario (Fig. 1). The rocks are part of the 2719-2710 Ma Kidd-Munro assemblage of the Abitibi greenstone belt (Ayer *et al.,* 2002a, b), which in this area comprises mainly mafic and ultramafic metavolcanic rocks, minor felsic metavolcanic rocks, and lesser pelitic metasedimentary rocks (Davis, 1997, 1999; Houlé *et al.*, 2002a,b). The rocks are macroscopically folded and locally faulted, but the strain was strongly partitioned, so the degree of penetrative deformation within most units is quite low. The metamorphic grade is lowermost greenschist facies (Jolly, 1982).

Figure 2 is a simplified geological map of the "Dundonald Beach" area. The volcanic-sedimentary sequence in this area dips and faces towards the south, and it comprises a lower unit of felsic volcaniclastic rocks overlain by a series of komatiitic basalts and komatiites. The units in the western part of the outcrop are thicker (up to 10m) and better differentiated with olivine and pyroxene spinifex-textured upper zones and pyroxene and olivine cumulate lower zones. Eastward along strike these units become much thinner (1-3m) and grade into the fine-grained, massive komatiitic basalt sills, peperites, and graphitic metasedimentary rocks described by Davis (1997, 1999), Houlé *et al.* (2002a,b, submitted), and Cas *et al.* (2001, 2003). The komatiitic basalts rocks are overlain at both ends of the outcrop by thicker, more massive olivine cumulate komatiite units, which contain the high-grade, low tonnage Ni-Cu-PGE mineralisation described by Muir and Comba (1979), and, in the western part of the outcrop, the spinifex-textured unit that is the subject of this paper. The upper part of the sequence is composed of another series of thick differentiated komatiitic basalts.

Field relations

The spinifex-textured komatiite sill described in this paper is exposed at the southern margin of the outcrop along a strike length of ~150m (Fig. 2). In the southwestern part of the Dundonald Beach outcrop (see Fig. 2), it is ~6m thick and comprises a 1.2-1.5m thick upper olivine spinifex-textured zone underlain by a ~3.5m thick lower olivine cumulate zone (Fig. 3). In the part of the outcrop immediately east of this area (see Fig. 2), the outcrop is less massive, but the sill is also ~6m thick and contains only a very thin (~0.5m) upper olivine spinifex-textured zone. It is overlain by another unit (only partly exposed along the southern margin of the outcrop shown in Fig. 3) of similar thickness, but with a fine-grained upper random olivine spinifex-textured zone containing abundant amygdales. In the southeastern part of the Dundonald Beach outcrop (see Fig. 2) the sill is composed almost entirely of olivine cumulate, clearly transgresses underlying komatiitic basalts, and hosts small amounts of very high tenor Ni-Cu-PGE mineralization. The upper contact in this area is sheared, but appears to be capped by a thin zone of peperite.

The lower contacts of the sill are not as well exposed as the upper contacts, partly because they have been trenched for Ni-Cu-PGE mineralization. In the area shown in Figure 3, an interval of fine-grained peridotite separates the olivine cumulate from the underlying komatiitic basaltic unit. A thin layer of shale occurs sporadically along the contact. The fine-grained peridotite is poorly exposed and highly weathered and was not sampled.

The contact between the olivine cumulate of the overlying unit and the top of the komatiite sill is slightly curved and has a gentle convex-upward form (see upper left part of Fig. 3). The transition from the olivine cumulate in the lower part of the overlying unit to the spinifex-textured rock in the upper part of the sill is sharp, and there is no indication of chilling or thermal metamorphism along the margins of either unit. The texture of the olivine cumulate at the base of the overlying unit is uniform right down to the contact (Figs. 5 and 6).

The uppermost part of sill is a very fine grained dark grey-green rock containing, within one centimetre of the contact, millimetre-sized polyhedral olivine grains (Fig. 5a and Layer 1 in Fig. 6). The dimensions of the olivine grains increase rapidly downwards into the unit, and at a distance of only 5 cm from the contact, the rock consists of stubby, randomly oriented, centimetre-sized skeletal olivines in a fine-grained groundmass of pyroxene and altered glass (Figs. 5 and Layer 2 in Fig. 6).

The textures, particularly the morphologies of the olivine crystals, vary considerably within the spinifex zone. From top to base there is a transition from a thin upper zone of randomly oriented bladed olivines (Fig. 4), through a zone composed of "books" of parallel platy olivines (Fig. 5b), to a zone of coarse dendritic olivines (Fig. 5c). This texture, which appears to be peculiar (in this area) to the sill, consists of large (up to 20 cm long and 1 cm wide) olivine dendrites that are sparsely distributed and randomly oriented within a matrix of finer platy olivines, pyroxene needles, and altered glass. The texture of this and other units are described in detail below.

The B1 zone, a layer of horizontally-oriented olivine tablets between the spinifex and olivine cumulate zones, is about 10 cm thick and planar. It is oriented parallel to the overall strike of the magmatic and sedimentary units (Figs. 2 and 3), which indicates that it was horizontal when deposited. The divergence between the orientation of the B1 zone and that of the upper contact contrasts with the undulating nature of the upper surface of the komatiite unit, suggesting that the latter is a magmatic, rather than structural, feature.

The olivine cumulates in the sill and the overlying unit have an identical, relatively uniform, fine-grained mesocumulate texture comprising >60% olivine in a matrix of fine-grained acicular pyroxene and altered glass.

Textural variations

Upper contact zone (sample DUN1)

Textures at the upper contact are illustrated in a photo of the contact in outcrop (Fig. 4b), a scanned image of a large thin section (Fig. 5a), a mosaic of photomicrographs (Fig. 6a), and a drawing of the olivine grains (Fig. 6b). At all of these scales, the texture in the olivine cumulate zone of the overlying unit remains uniform all the way down to the contact. In a band only 5-10 mm wide and immediately above the contact, the matrix between the olivine grains has a slightly darker colour, but it is not clear whether this is due to baking from the komatiite sill or enhanced alteration related to focused fluid circulation along the contact. The olivine cumulate above the contact contains 60-70% solid, sub-equant, sub-millimeter olivine crystals, and rare larger grains, in a matrix of fine-grained pyroxene and very fine-grained altered brown glass. Most of the olivine grains are altered to serpentine or chlorite, but in irregularly-distributed patches many of the grains remain unaltered.

The uppermost centimetre of the sill contains sub-equant, moderately to highly skeletal grains of olivine in a matrix of fine olivine wafers, acicular pyroxene grains, and altered brown glass (Figs. 4-6). The contact is inconspicuous, even at the thin-section scale. It is not marked by a fracture or suture, nor by a zone of chilling. Instead, there is a marked *increase* in the size of the olivine grains, from ~0.5 mm in the overlying olivine cumulate, to 1-5 mm in the uppermost margin of the sill. The larger olivine grains have distinctive shapes and orientations: at the contact, they are solid, subhedral, and non-skeletal, and downward over a distance of a few mm, the habit changes from solid to skeletal. The transition is well illustrated in the grain just right of centre in Figure 6a: as shown in Figure 7b, it has a sub-vertical orientation, a euhedral, slightly skeletal morphology at its base, and appears to be rooted in equant cumulus olivine grains at the top. This grain apparently nucleated on the olivine grains at the base of the overlying unit and grew downward into the liquid of the sill. Deeper in the sill, but still within 2-3 cm of the upper contact, the olivine grains have a well-developed “hopper” morphology. They are relatively stubby (aspect ratio ~2-4) with highly skeletal, ribbed interiors and, in some cases, distinctive parabolic “snouts” (Fig. 5b, 7a). With the exception of chromite, all magmatic minerals in the upper contact zone have been totally replaced by secondary minerals.

In contrast with the textures in the olivine cumulate of the overlying unit, which are uniform, the olivine grains in the upper border zone of the sill have characteristic sizes and morphologies that change with distance from the contact, as described above. The border zone itself maintains a relatively constant thickness and follows the gentle undulations of the contact.

Random (DUN2) and platy (DUN3) olivine spinifex-textured zone

The textures in these zones are similar to those in many komatiite lava flows. Random olivine spinifex texture (Fig. 4b) consists of ~50% randomly-oriented, fine to coarse (0.5-7 cm) moderately-skeletal olivine blades in a matrix of fine-grained pyroxene grains and altered glass. The pyroxene grains have an acicular habit and are zoned from pigeonite cores (now altered to chlorite) to augite margins. Platy olivine spinifex texture (Fig. 5b) consists of ~40% coarse (1-2 cm wide, 5-10 cm long) parallel books of moderately-skeletal olivine wafers in a similar matrix. The books are oriented in a near-random manner, but more commonly closer to parallel than perpendicular to the top of the unit.

Coarse dendritic spinifex-textured zone (DUN4)

This name is given to a texture that has not previously been described in the literature. The dominant element of the texture are very large olivine crystals, several centimetres long and up to a centimetre wide, with a highly complex internal structure (Figs. 4b, 5b). These crystals commonly have a fine parabolic snout at one end (Fig. 5b, 7a), a characteristic feature of dendrites. In the centre of each crystal, complexly-ribbed cells have grown outward from a central spine. The crystals are relatively sparsely distributed and randomly oriented in a matrix of finer platy olivines, acicular pyroxene grains, and altered glass. All of the olivine is altered to serpentine or chlorite, but magmatic pyroxene is preserved in patches in the groundmass. Similar textures occur in thick komatiite flows, komatiitic sills, and komatiitic dykes at several other localities (e.g., Kambalda, Western Australia; Eldorado Township, Ontario; McArthur Township, Ontario).

B1 zone (DUN5)

As in some (but not all) spinifex-textured lava flows, the spinifex zone is separated from the olivine cumulate zone by a 5-10 cm thick layer containing fine, slightly skeletal tabular olivine grains oriented parallel to the upper contact of the sill (Fig. 5c). Many of the large dendritic olivine crystals in the lowermost part of the spinifex zone are oriented at a high angle to the B1 layer. Some appear to have nucleated on B1 olivine grains and to have grown upwards into the overlying sill, indicating that the B1 zone formed prior to crystallization of the lowermost part of the spinifex zone (e.g., Pyke *et al*., 1973; Arndt, 1986; Lesher and Keays, 2002).

Olivine cumulate zone (DUN6, 8, 9)

The olivine cumulate of the komatiite sill is very similar to that of the overlying unit (see description above) and to the cumulate zones of many komatiite lava flows. One difference between the sill and the overlying unit in this locality is the presence in the cumulate zone of the sill of irregular, centimetre-sized patches within which the olivine grains have a skeletal morphology. In some of the patches, the grains have an elongate tabular form and the texture is very similar to random spinifex texture. As in the overlying unit, olivine grains in irregular regions are unaltered.

Chemical compositions

Major and trace element compositions of whole rock samples are provided in an electronic data file. MgO contents range from 24 to 28% in spinifex-textured lavas and from 38-42% in olivine cumulates. Al_2O_3/TiO_2 ratios are similar to, or slightly higher than, the chondritic value of 20. Heavy rare-earth element ratios also are chondritic and the light rare-earth elements are depleted. These features are typical of komatiites throughout the Abitibi belt (Arth *et al.* 1977; Sun 1984; Xie *et al.* 1993; Sproule *et al.,* 2002).

Discussion

Environment of emplacement

The graphitic, framboidal sulfidic sediments in the Dundonald area (Muir and Comba, 1979; Houlé *et al*., 2002a,b, 2004a) indicate a deep-water environment of deposition for those rocks and the fluidal and blocky peperites in the lower part of the stratigraphic sequence (Fig. 2) indicate that the sediments were unconsolidated when the komatiitic rocks were emplaced. The very fine-grained skeletal pyroxene and altered glass in the mesostases of all of the rocks, including the cumulates, indicates rapid cooling. Together, these features provide evidence that the komatiitic units were emplaced in or on a series of unconsolidated sediments close to or at the ocean floor.

Discrimination between komatiite flows and sills

Dann (2000) presented a number of features that can be used to distinguish between komatiite lava flows and sills. Many of these apply specifically to the volcanic sequence in the Barberton greenstone belt and are based on relations between komatiite and pillow lava, so they are not applicable in this area. Of the others, the most useful are the presence of flow-top breccias and hyaloclastites, vesicular flow tops, and pipe vesicles in lava flows. He also mentions the specific form of an inflated lava flow, in which an upward domed roof overlies a thickened portion of the flow. As the only feature diagnostic of a sill he cites locally cross-cutting relationships with the host rock. In the following section, we discuss these features and present others that we believe are diagnostic in evaluating the volcanic setting of the komatiites at Dundonald Beach.

Flow-top breccias: The upper surfaces of lava flows are in direct contact with air or water and cool much more rapidly than the upper contacts of sills. As a consequence, many komatiite flows are capped by characteristic flow-top hyaloclastite breccias containing shard- or bubble-wall fragments and a wide variety of quench textures (e.g., Munro Township: Pyke et al., 1973; Arndt, 1976; Alexo: Barnes and Naldrett, 1986; Arndt, 1986; Kambalda: Thomson, 1989; Zwishevane: Renner et al., 1993). Even where hyaloclastites have not formed, lava flows are characterized by relatively thick upper chilled margins containing sparse, small and highly skeletal crystals and abundant volcanic glass. The upper margins of sills, in contrast, are in contact with poorly-conductive solid rocks, cool much less rapidly, and should form less glass. Where present, flow-top breccia and aphanitic upper chilled margins provide unequivocal evidence of an extrusive origin.

Polyhedral jointing: Many komatiite flows, including some at the classic Barberton (Viljoen and Viljoen, 1969; Dann, 2001) and Munro Township (Pyke *et al.* 1973) localities, do not have extensive flow-top breccias. Upper chilled margins may be present in both lava flows and sills, but they are thicker in lava flows and are cut by distinctive polyhedral joints (Figs. 4, 8). How deep the polyhedral joints penetrate into the flow depends on several factors, including the thickness of the flow and whether the flow is immediately covered by another flow. Thinner flows tend to have relatively thick zones of polyhedral jointing and very thin flows may be polyhedrally jointed throughout. Rapidly-emplaced units have thinner zones of polyhedral jointing. Where present, polyhedral jointing provides unequivocal evidence of an extrusive origin.

Grain-size variations: Because of differences in cooling rates, at given distances from the tops of sills, the crystals should be larger, less elongate, and less skeletal than those at a similar positions in lava flows (Fig. 8).

Lower chilled margins. Although the upper chilled margin of a flow may be removed by thermomechanical erosion from an overlying flow or sill, a lower chilled margin can only be removed by intrusion from below. If the textures in the lower part of the unit remain uniform right down to the contact between the two units, with no evidence of an increase in the proportion of glass or the appearance of quench crystals that marks a chilled lower contact, the contact is most likely intrusive. Importantly, however, sills commonly intrude along the contacts between units, so the *presence* of a lower chilled margin cannot be used to *discount* intrusion.

Transgressive upper contacts: Although the lower contacts of both lava flows and sills may be transgressive, the upper contacts of flows cannot be transgressive. If the komatiite unit or apophyses cut across the structure of the overlying unit, there is no doubt that the komatiite unit was emplaced later and is therefore intrusive.

Baked contacts: Similarly, both lava flows and sills may bake underlying rocks, but a flow cannot bake the rocks that overlie it unless the overlying flow was emplaced before the underlying flow cooled completely. If these rocks are significantly baked (thermally metamorphosed) there is no doubt that the komatiite unit was intrusive.

Peperitic textures: Peperites form by disintegration of magma intruding and mingling with unconsolidated, typically wet sediments (White *et al.* 2000; Skilling *et al.* 2002). Peperitic textures may form along the upper and lower margins of sills, but not along the upper contacts of lava flows. The presence of peperite along the upper margin of a unit is unequivocal evidence for an intrusive origin.

Overall form and relationship with surrounding rocks. The upper surfaces of lava flows are free and easily deformed, and their lower surfaces conform to the underlying topography, which may also be irregular. When new magma flows into the interior, the roof of the flow may rise, producing a characteristic domed form (e.g., Dann, 2000), or lava may break out from the flow to form a separate unit. In either case, the upper and lower surfaces are irregular on an intermediate to large scale and the overlying rocks are undeformed. If a sill intrudes along a plane of weakness into solid, brittle rocks, it will be planar and its upper and lower margins should match. However, if magma intrudes at shallow depth into unconsolidated sediments, the intruded material may deform and the upper surface of the intrusion may be domed and irregular. Lava flows and sills may both be planar and concordant, and flows and sills may both thermomechanically erode underlying rocks, but only flows can have irregular or domed upper surfaces that have not deformed overlying rocks.

Features indicative of an intrusive origin for the komatiite unit at Dundonald Beach

Based on the above discussion, we can now summarize the evidence for an intrusive origin for the spinifex-textured sill at Dundonald Beach:

1) There is no lower chilled margin at the base of the overlying unit. Textures in the olivine cumulate zone of the overlying unit are uniform all the way down to the lower contact, with no sign of chilling at the base. The olivine cumulate zone of the overlying unit is interpreted to have been truncated during intrusion of the underlying sill.

2) There is no sign of chilling or other flow-top structures along the upper contact of the sill. In contrast, the grains immediately below to the upper contact are solid and polyhedral to rounded, and they are distinctly larger than the olivine grains in the cumulate zone of the overlying unit. These grains give way downwards to large (5-10 mm), equant, highly skeletal hopper olivine grains with unusual morphologies, as illustrated in Figures 4 to 6. Breccias, polyhedral joints, and other structures characteristic of lava flows are absent.

3) The variations in grain sizes are quite different from those observed in typical komatiite lava flows (Fig. 8: left side), which have a relatively thick (~7 cm) aphanitic zone in which no crystals are visible in hand samples, underlain by a thick (~ 15 cm) random spinifex textured zone in which the average length of the olivine blades gradually increases from about 0.6 mm to 4.5 mm, underlain by a platy spinifex zone of variable thickness, which contains books with an average length exceeding 10 mm. The grain size variations in the upper part of the komatiite sill are quite different (Fig. 8: right side). Even in the uppermost centimetre of the unit, individual olivine grains are visible and have an average length of 0.7 mm. At a depth of 0.5 to 6 cm, the average length of random spinifex-textured olivine crystals varies from 2.8 to 8.5 mm. In komatiite flows, this grain size is only reached at a distance of about 25 cm from the top of the unit. Deeper in the sill, at a depth of about 30 cm, the grain sizes are about the same as those in the flow. The differences between a flow and a sill are less pronounced in the interior because, once a

solid crust has formed at the top of the unit, the cooling conditions are very similar. In both cases, if olivine phenocrysts have had time to accumulate (via settling or *in situ* crystallization), a lower olivine cumulate layer develops and spinifex textures form through downward crystallization of olivine (or pyroxene) in the thermal and chemical gradient in the liquid just beneath the solid crust (Faure *et al.* 2001).

4) Vesicles are most abundant in a zone within 1 cm of the upper contact of the sill. The largest vesicles occur at a distance of 2-3 mm from the contact, and immediately adjacent to the contact there are only a few, smaller, sparsely distributed vesicles. Some of the vesicles are filled with quenched silicate liquid, which apparently drained into the vesicles during cooling (Fig. 7d); others are filled with secondary minerals (Fig. 6). A chilled zone containing abundant small vesicles, as might form during the quenching of lava, is absent. Although it is possible that the upper part of the unit may have been melted, destroying any previous vesicles, the present distribution is consistent with the komatiite sill being intrusive into the overlying unit. Beresford *et al.* (in preparation) have shown that the komatiitic units in the eastern side of the outcrop (Fig. 2) commonly have vesicular tops and they demonstrated using geological relations and textures that the volatiles were derived through interaction between the komatiite magma and unconsolidated, water-rich sediments.

5) The komatiite sill directly overlies a series of thinner komatiitic basalt units that clearly intruded into a sequence of unconsolidated sediments (Davis, 1997, 1999; Houlé *et al.* 2002a, b, 2004a; Cas *et al.* 2003).

The possibility that the two units in Figure 3 erupted rapidly enough to impede the formation of chilled margins between the units was considered, but the grain size variations (Fig. 8) and absence of polyhedral jointing militate against such an interpretation. In places where the structures and textures of the lavas indicate that they have been emplaced as compound lava lobes in rapid succession (e.g., Pyke Hill), the boundaries between flows are defined by the 10-20 cm thick aphanitic upper polyhedrally-jointed zones in the underlying flows and 2-5 cm thick aphanitic lower chilled margins in the overlying flows (Pyke et al., 1973). In the Dundonald units, in contrast, the thickness of the upper fine-grained margin is less 1 cm and there is no chill whatsoever at the base of the overlying unit.

We have also considered the possibility that the komatiites on Dundonald Beach, which are thicker and contain a greater proportion of olivine cumulate rock than those on Pyke Hill, may represent magma conduits and remained hotter for a longer period of time than thinner flows, thereby impeding the formation of chilled margins. However, even very thick (up to 100m) thick olivine cumulate lava channels and channelized sheet flows in the Kambalda area exhibit well-defined upper and lower aphanitic margins (Lesher et al. 1984; Lesher, 1989).

Finally, the possibility that the komatiites on Dundonald Beach represent beheading and changing crystallization dynamics in a reactivated lava channel complex, analogous to the interpretation for internal zones of branching crescumulate olivine and vesicular zones within the thick olivine mesocumulate lava channel complexes at Kambalda (Lesher et al., 1984; Cowden, 1988; Lesher, 1989) was also considered. However, the compound units at Kambalda do not contain *internal* chilled margins or spinifex-textured rocks like those at Dundonald Beach and, as argued below, the textures within the lower unit in Figure 3 suggests emplacement from below, not from above. For these reasons, we prefer to interpret the contact between these units as intrusive and attribute its irregular nature to thermomechanical erosion of the hot lower part of the overlying unit during intrusion of the lower unit. Along strike the lower komatiitic unit clearly cuts down into the underlying komatiitic basalt units (Fig. 2).

On the basis of all these arguments, we conclude that the komatiite unit that is the subject of this paper, and most if not, all of the other komatiitic rocks in the Dundonald Beach area, are best interpreted as a series of interfingering, mainly concordant intrusions.

Interpretation of textures in the upper part of the sill

The textures and olivine habits in the upper part of the komatiite sill are highly unusual and require further explanation. More specifically, we need to account for the lack of chilling at the upper margin of the sill and in the lower margin of the overlying unit, the lack of evidence of baking and other thermal effects, the large size and polyhedral habit of the olivine grains immediately below the contact, and the change in habit of olivine and chromite grains within the spinifex zone. We must also explain the changes in olivine morphologies from the upper contact zone of the komatiite sill; from relatively large (compared with cumulus olivines of the overlying unit) subhedral to rounded, solid polyhedral olivine (Layer 1 in Figure 6) → highly skeletal, subequant hopper olivine (Layer 2) → skeletal bladed olivine in the random spinifex layer → large parallel olivine plates and coarse dendrites in the lower part of the spinifex layer (Figs 4, 5). All of these features can be explained if we take into account the mechanisms of nucleation and crystal growth in silicate liquids, and the likely temperature distribution in the sill immediately after its emplacement.

From the work of experimental petrologists, particularly Donaldson (1978, 1982), we know that the morphology of olivine crystallizing in rapidly cooled mafic-ultramafic magmas depends primarily on a) the cooling rate and/or degree of undercooling, b) the nucleation mechanism, and c) the composition of the liquid. Slow cooling or crystallization from modestly undercooled liquids results in polyhedral olivine morphologies; faster cooling or crystallization from highly undercooled liquids leads to more elongate and more skeletal grains. Because of differences in viscosity and melt structure, at a constant cooling rate, olivine that crystallizes in basaltic magma has a more skeletal and elongate habit than olivine crystallizing in ultramafic magma. Faure *et al.* (2001) have demonstrated that when olivine crystallizes within a thermal gradient, such as along the margin of a flow or sill, the olivine grains acquire a preferred orientation and have a more skeletal habit than olivine that crystallizes in the absence of a thermal gradient. Finally, pre-existing crystals act as nuclei and lead to the growth of crystals with less skeletal morphologies than those that nucleate homogeneously (Lofgren, 1983).

Figure 9 shows the results of modelling the evolution of temperatures in the sill and the overlying units. The parameters used in the models are given in the figure caption. Although a chilled margin forms immediately after emplacement, it is immediately remelted as heat is transferred from the sill to the overlying rock. Twenty seconds after emplacement, the temperatures in the silicate liquid within a few millimeters of the contact are significantly below the liquidus, and a mm-wide zone of supersolidus temperatures, a zone of partial melt, has formed at the base of the overlying unit. Sixty minutes after emplacement, the zone of sub-liquidus temperatures extends several centimeters downward into the sill and the partially molten zone in the overlying unit is about 1 cm thick. The textures in the rocks at both sides of the contact, and particularly the morphologies of the olivine grains, can be explained by the temperature variations shown in the figure. The irregular nature of the contact and especially the embayments filled with liquid from the sill (labelled “e” in Figure 5a) and the presence of isolated packets of olivine grains at the base of the olivine cumulate (labelled “p” in the same figure) result from partial melting at the base of the overlying unit. The randomly-oriented hopper olivine crystals in the upper few centimeters of the sill nucleated homogeneously and grew from moderately- to highly-undercooled liquid in the upper part of the sill. The large solid polyhedral crystals in Layer 1, immediately below the contact (Figure 6a and b), nucleated heterogeneously and grew on the olivine grains in the overlying cumulate rock. The platy and coarse dendritic spinifex crystals deeper in the sill grew later, at lower cooling rates in a thermal gradient, conditions that Faure *et al.* (2001 and in preparation) have shown lead to constrained growth, elongate morphologies, and preferred orientations.

Intrusive komatiites and the water contents of komatiite liquids

Grove, de Wit, Parman, and co-workers have argued in a series of papers (Grove *et al.* 1994, 1996, 1999; Parman *et al.* 1997) that komatiites in the Barberton belt, South Africa, were emplaced as sills at a depth of about 6 km. They proposed that the parental komatiite magma contained up to 6% H_20, and that this magma crystallized within the sills before all the H_2O had escaped. They attributed the growth of spinifex textures and the compositions of calcic pyroxene interstitial to olivine in spinifex-textured rock to crystallization in a hydrous magma at a pressure of about 0.2 GPa. Although the possibility of an intrusive origin for some of these units has since been eliminated by the detailed mapping of Dann (2003), the theory remains correct. If a hydrous magma becomes trapped within the middle to upper crust, the magma may crystallize before the H_2O escapes. If, on the other hand, the komatiite erupts at the surface as a lava flow, the low solubility of water at low pressure and the very low viscosities of komatiite magmas should provoke rapid degassing of the lava (Arndt *et al.* 1998; Green 1974; Cashman & Blundy, 2000). Parman *et al.* (2001) and Dann (2001) have suggested that sluggish kinetics may inhibit degassing, citing as evidence certain boninites that appear to have erupted as non-vesiculated magmas and that contain glass with up to 6% H_2O. These authors suggest that hydrous komatiite may also erupt in a non-equilibrium, non-degassed state. How does our study of the Dundonald komatiites, and of komatiites in other parts of the Abitibi belt, contribute to the problem?

A high-Mg unit in Boston Township, ~100 km southeast of Dundonald (Fig. 1), has a very peculiar chemical composition, being unusually rich in Fe, Ti, and highly incompatible trace elements. Stone *et al.* (1987, 1997) identified magmatic amphibole in several samples from this unit and argued that the magma originally contained 1-2% H_2O. This magma appears to have formed through low-degree melting of a slightly hydrous, chemically anomalous part of the mantle. Detailed mapping of the upper contact of this unit by Houlé *et al.* (2004b) indicates that its upper contact is intrusive in two separate locations: apophyses from the upper chilled margin transgress overlying rocks and the upper margin contains fragments of the overlying rocks. There is little doubt that this komatiite contained a small amount of H_2O and that it was emplaced as sill. Although it remains possible that the H_2O was acquired locally, by assimilation of sediments, it is likely that a picritic magma enriched in Fe, Ti and incompatible trace elements was derived from an enriched, hydrous source.

In contrast, the intrusive komatiites in Dundonald, like most komatiites in the Abitibi belt (Sproule et al., 2002) and other late Archean belts, are strongly depleted in highly incompatible lithophile elements (e.g., U, Th, Nb, Ta, LREE). As noted by Arndt *et al.* (1998) unless the magma was systematically enriched in H_2O relative to these other elements, it must have been essentially anhydrous. The komatiite sill does contain vesicles, but they are very sparse (always less than 1% of the rock) and are confined to the uppermost part of the unit, consistent with only minor volatile contents.

Other constraints on the initial water content of the magma come from more involved arguments. Although these komatiites are intrusive in the strictest sense of the term, they erupted very close to the ocean floor. Houlé *et al.* (2002a,b, 2004a) and Cas *et al.* (2003) demonstrated quite clearly that some of the komatiitic basaltic units below the komatiite sill invaded unconsolidated and water-saturated sediments, suggesting that dense komatiite magma rose through the crust until it encountered a layer of weak, low-density sediment, which it intruded instead of continuing to the surface. It is difficult to judge the thickness of the sediment pile, but based on the minor amount of sediment in the sequence, it is unlikely to be more than a few hundred metres. Even if we add the pressure imposed by several kilometres of ocean water, the total pressure is unlikely to have reached 0.1 GPa. Komatiite magma can dissolve no more than a few hundred ppm H_2O at equilibrium under these conditions. Parman *et al.* (2001) and Dann (2001) have suggested that the water-rich magma might have been emplaced in a metastable state, unable to nucleate and degas, but as noted above, sills crystallize more slowly than flows, so water would be more likely to have nucleated in sills than in flows, facilitating exsolution and accumulation beneath the cap of overlying olivine cumulate rock, forming highly vesicular zones or large gas cavities, as observed in the upper parts of continental flood basalts (Self *et al.* 1997). This picture is in marked contrast to the very sparsely vesicular nature of the upper part of the Dundonald komatiite sill. As mentioned earlier, the vesicular upper parts of the komatiitic unit in the eastern part of the outcrop are attributed by Beresford et al. (in preparation) to interaction between the komatiite magma and the enclosing unconsolidated sediments.

In the case of lava flows, it is conceivable that the magma lost volatiles during lava fountaining and that the lava flows subsequently crystallized from degassed lava. Such an interpretation is at odds, however, with the rarity of vesicular, scoriaceous, or fragmental komatiite in the Abitibi belt and elsewhere. The fragmental komatiites at Scotia (Page and Schmulian, 1981), in Finland (Saverikko 1985) and on Gorgona Island (Echeverria and Aitken 1986), which had been interpreted as pyroclastic deposits, are now interpreted as epiclastic deposits (Scotia) or hyaloclastites (Finland, Gorgona). In any case, because the Dundonald komatiites invaded unconsolidated sediments before reaching the surface, they would have had no opportunity to degas through lava fountaining.

Conclusion

On the basis of detailed field and petrographic study we conclude that the sill and underlying units are intrusive, formed from essentially anhydrous komatiite liquid emplaced in a volcano-sedimentary succession very close to the ocean floor. These rocks may therefore be considered as the hypabyssal component of the komatiitic volcanic series. Magmatically, they are identical to komatiite flows and they owe their intrusive origin only the nature of the rocks that they encountered on their way to the surface.

Acknowledgements

The field work for this project was supported by grants from the Jacques Cartier Centre in Lyon (to NTA) and the Natural Sciences and Engineering Council of Canada (to CML). We have benefited greatly from discussions in the field with Paul Davis, Harold Gibson, Phil Thurston, Ray Cas, and Steve Beresford. We thank Mike Higgins, François Faure, Marjory Wilson, and an anonymous reviewer for comments that helped us improve the manuscript.

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Figure captions

Fig. 1: Location of the Dundonald Beach area within the Abitibi greenstone belt, Canada (modified from Ayer *et al.*, 2002).

Fig. 2: Simplified geological map of the western part of the Dundonald Beach area (modified from Davis, 1999). The komatiite sill is the thick grey olivine cumulate unit near the top of the sequence; the part that was mapped in detail is identified as Fig. 3. The map is drawn with North downwards so that the volcanic stratigraphy is correctly oriented and corresponds to that of the geological sections.

Fig. 3: Simplified geological map of the western part of the komatiite sill and adjacent units.

Fig. 4: Comparison between textures developed in: a) a typical thin komatiite flow from Pyke Hill in Munro Township (Pyke et al., 1973), b) the Dundonald komatiite sill. In the sketch of the sill, the sizes of the olivine grains are not to scale; the smaller crystals are exaggerated to emphasize how their form varies, particularly at the upper contact.

Fig. 5: Textures at the upper contact and in the interior of the komatiite sill. a) Scanned image from part of a large thin section showing the upper contact of the komatiite sill (sample DUN1). The region labelled “e” is a protuberance of komatiite liquid up into the overlying unit and “p” is a region of accumulation of equant olivine grains from the overlying unit. b) Scanned polished surface of sample DUN4 showing a large dendritic olivine crystal and finer platy olivine crystals. The olivine is serpentinized and is dark green in the polished section. The volumes between the olivine plates are filled with acicular zoned pyroxene grains. The augite outer parts of some of these crystals are preserved, but the pigeonite cores are totally altered to chlorite. c) Scanned polished surface of sample DUN5 showing the large dendritic olivine crystals at the base of spinifex layer and horizontal tabular crystals at the top of the B1 zone.

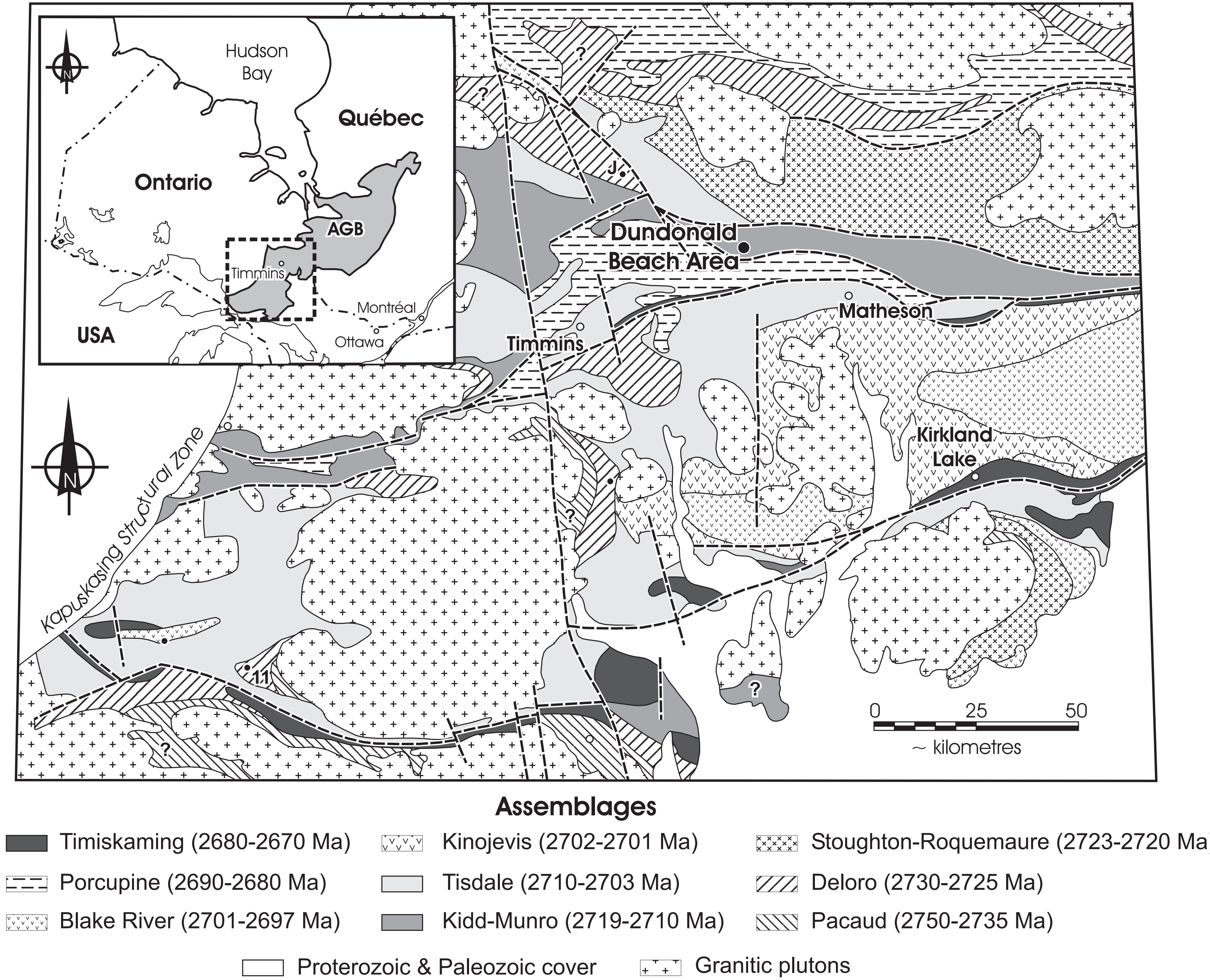
Fig. 6: a) Mosiac of photomicrographs showing in detail the upper contact of the sill. b) Sketch of Fig. 6a. Only grains with sharp black outlines were sketched accurately; those in the olivine cumulate with diffuse outlines are shown only schematically. Note the following features: the uniform texture of the lowermost part of the olivine cumulate zone in the overlying unit; the irregular contact; the presence of a layer of large, solid olivine grains just below the contact (Layer 1); the transition to larger equant hopper grains within 1 cm of the contact (Layer 2); and the presence of vesicles near the contact.

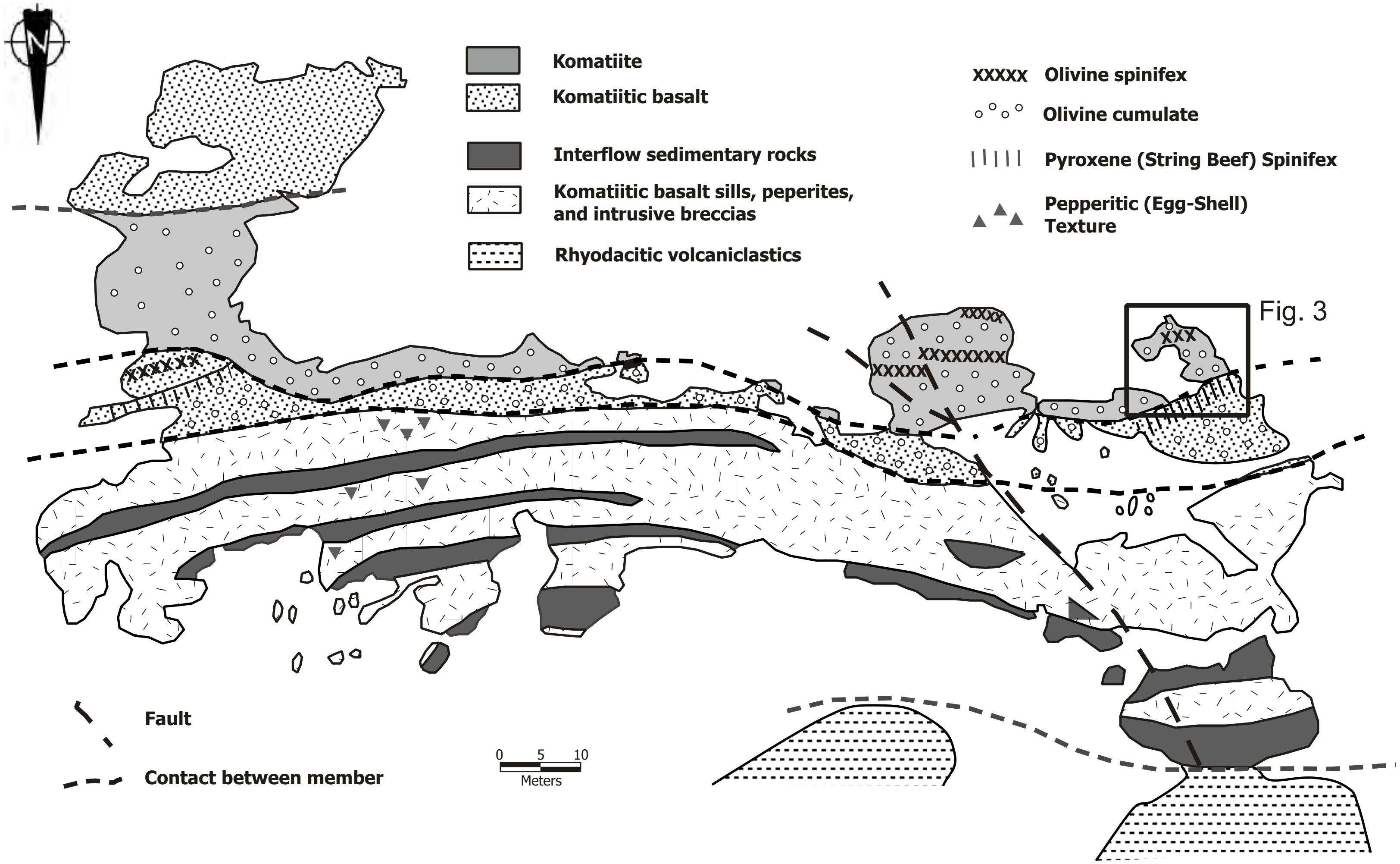
Fig. 7: Photomicrographs of textures in the upper contact zone of the sill. a) Dendritic olivine grain with a parabolic “snout”. b) A complex, vertically oriented olivine grain from DUN1 (Fig. 6). The upper part consists of large, rounded, solid grains and the lower part is tabular with skeletal overgrowths. Note the vesicle filled with secondary minerals in the top left. c) Chromite crystal with a solid euhedral upper portion (oriented towards the bottom left in the photo) and a skeletal lower portion. d) Segregation vesicle filled with interstitial melt.

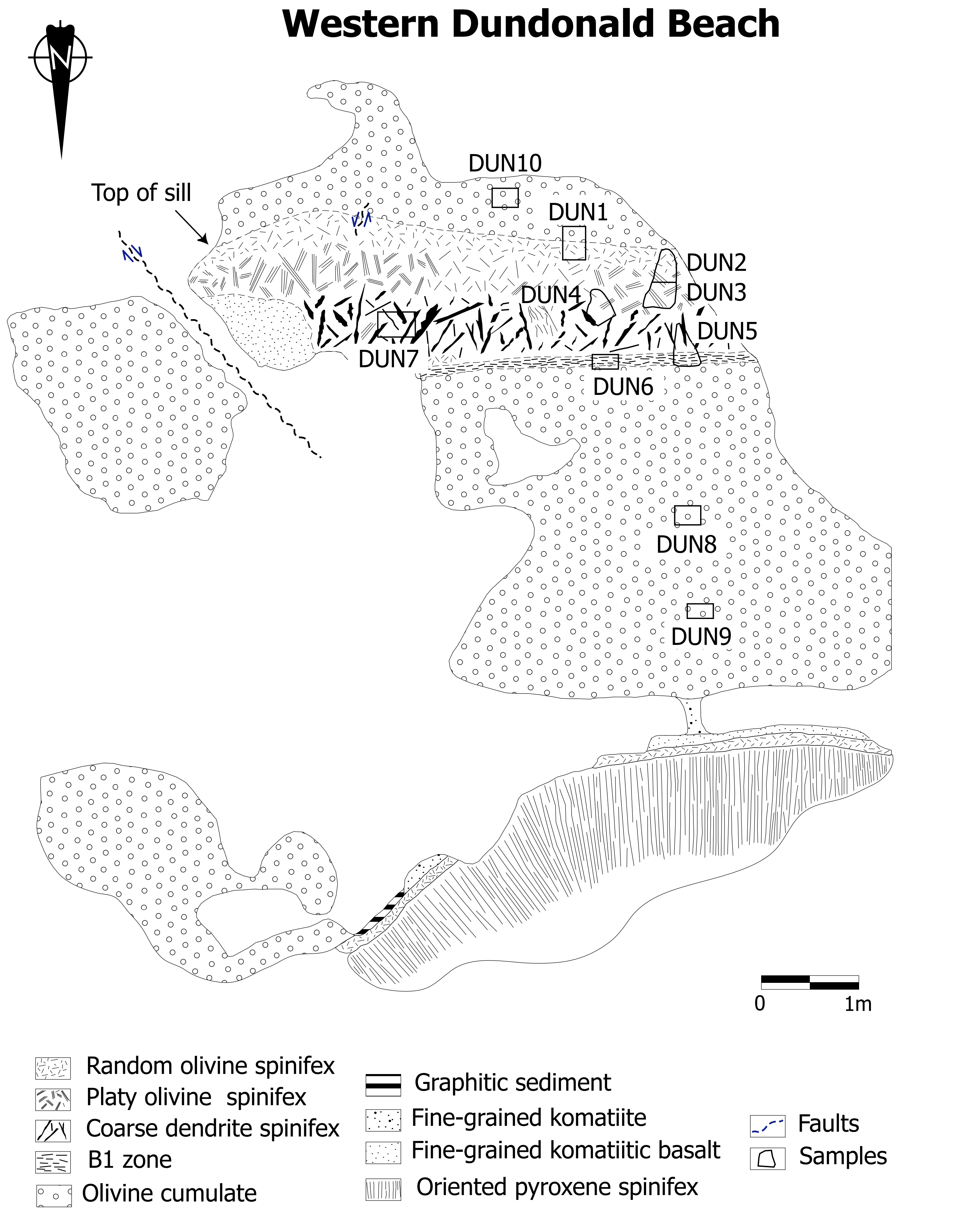
Fig. 8: Size distribution of long axes of olivine crystals, measured in images of outcrops or polished slabs, in the Dundonald komatiite sill (left) and a komatiite flow from Munro Township (right). The straight lines in the images represent the long axes of crystals. Arrows above the histograms indicate mean dimensions. Large crystals of olivine are present immediately below the top of the sill, but are absent in the upper part of the flow. For example, at a depth of 1 cm below the contact of the sill the average length is 2.8 mm; in

contrast, crystals with this average dimension are present only at a depth of about 15 cm in the flow. Below about 30 cm, the average crystal size is similar in the sill and the flow.

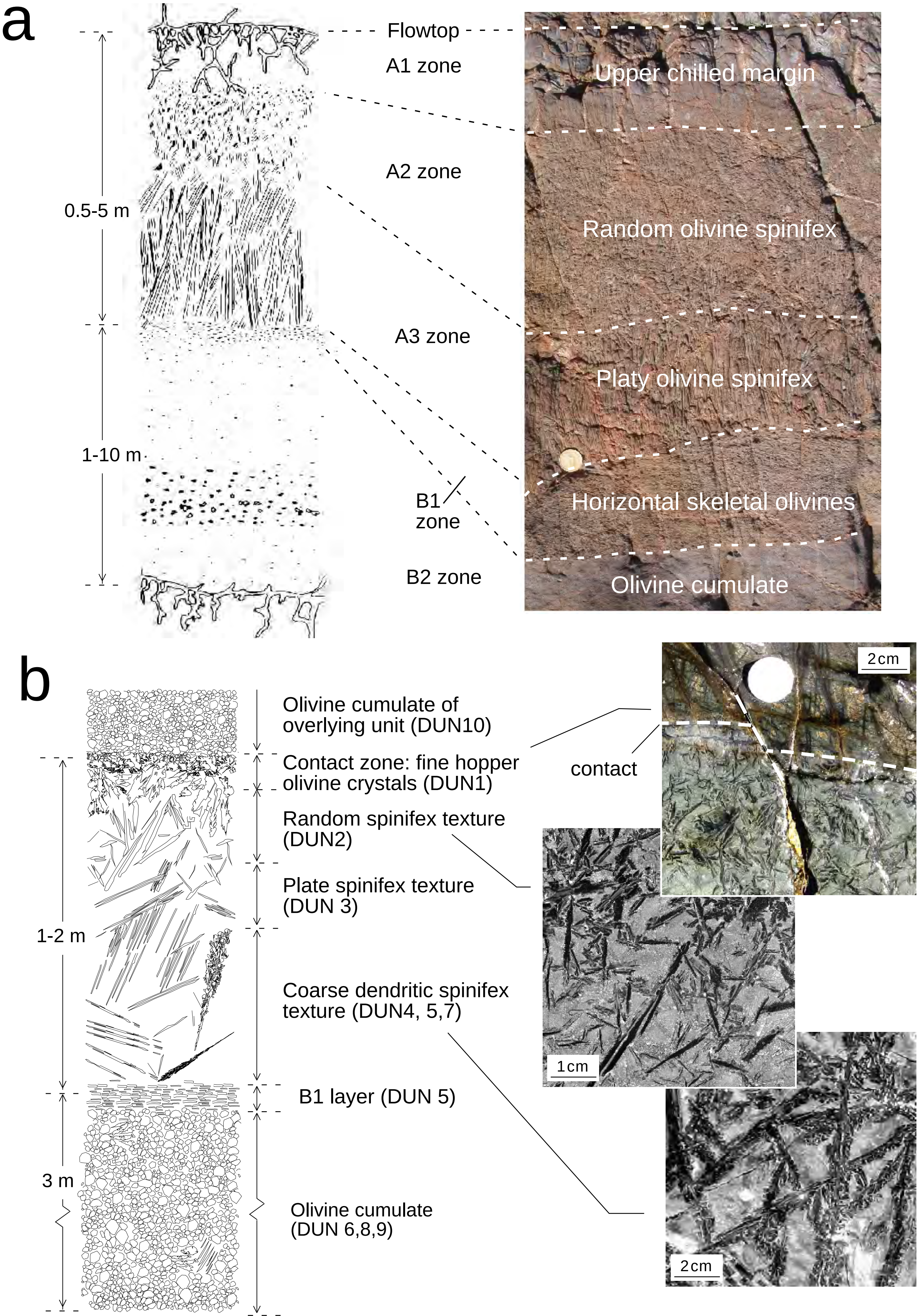
Fig. 9: Numerical solutions for temperature profiles across the contact between a komatiitic sill and the overlying unit, calculated at two different times: a) 20s after intrusion; b) 1 hour after intrusion. The numerical model has a simple 1D geometry with two infinite half-spaces; "negative" positions correspond to the overlying unit and "positive" to positions to the sill. It was assumed for simplicity that both units had the same composition — a komatiite with about 25% MgO. At the time of intrusion the upper unit was totally solid (T = 100°C) and the intrusion totally liquid (T = 1550°C); immediately after intrusion a “mush” zone formed in the upper part of the sill and a thin partially molten zone formed at the base of the overlying unit. The melt fraction in the mush zone is a simple linear-ramp relationship related to temperature, increasing from 0 for temperature at the solidus (T_{sld}=1150°C) to 100% for temperature at liquidus (T_{lqd}=1550°C). The temperature evolves through diffusive conduction and latent heat generation from crystallization or melting. The following physical parameters were used: heat capacity Cp=730 J/kg/K, latent heat L=0.42 MJ/kg. In the liquid, volumetric mass $\rho_L=2.8\cdot10^3$ kg/m^{-3}, heat conductivity λ_L=1 W/K/m, in the solid, $\rho_S=2.7\cdot10^3$ kg/m^{-3}, λ_S=0.005 W/K/m. In the mush, the heat conductivity was calculated as a simple linear expression of the solid and liquid values, weighted by mass fraction.

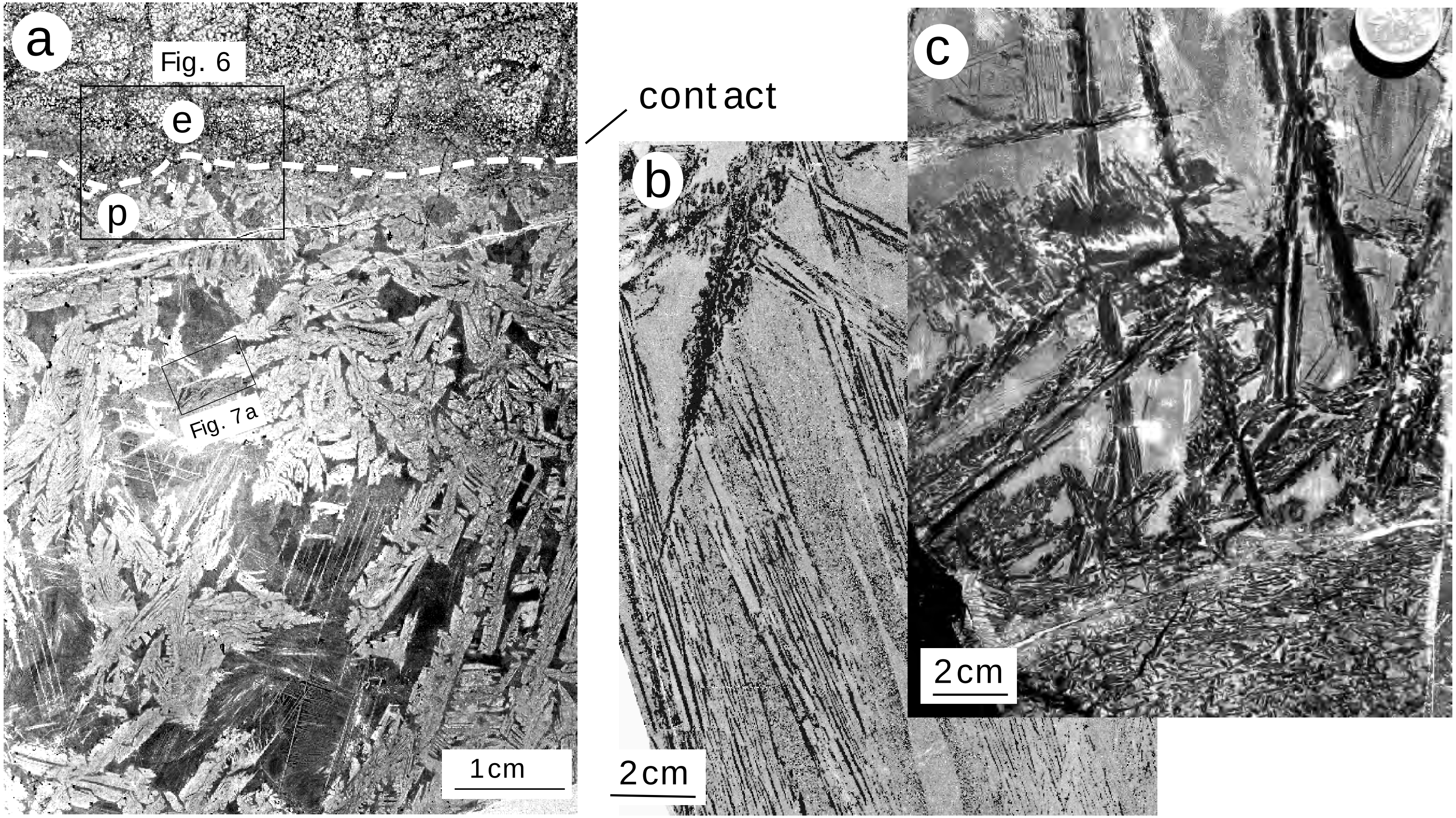

Hudson
Bay
Québec
Ontario
AGB
Timmins
Montréal
Ottawa
USA
N
Dundonald
Beach Area
Matheson
Timmins
Kirkland
Lake
Kapuskasing Structural Zone
J
11
?
0
25
50
~ kilometres
Assemblages
Timiskaming (2680-2670 Ma)
Porcupine (2690-2680 Ma)
Blake River (2701-2697 Ma)
Kinojevis (2702-2701 Ma)
Tisdale (2710-2703 Ma)
Kidd-Munro (2719-2710 Ma)
Stoughton-Roquemaure (2723-2720 Ma)
Deloro (2730-2725 Ma)
Pacaud (2750-2735 Ma)
Proterozoic & Paleozoic cover
Granitic plutons

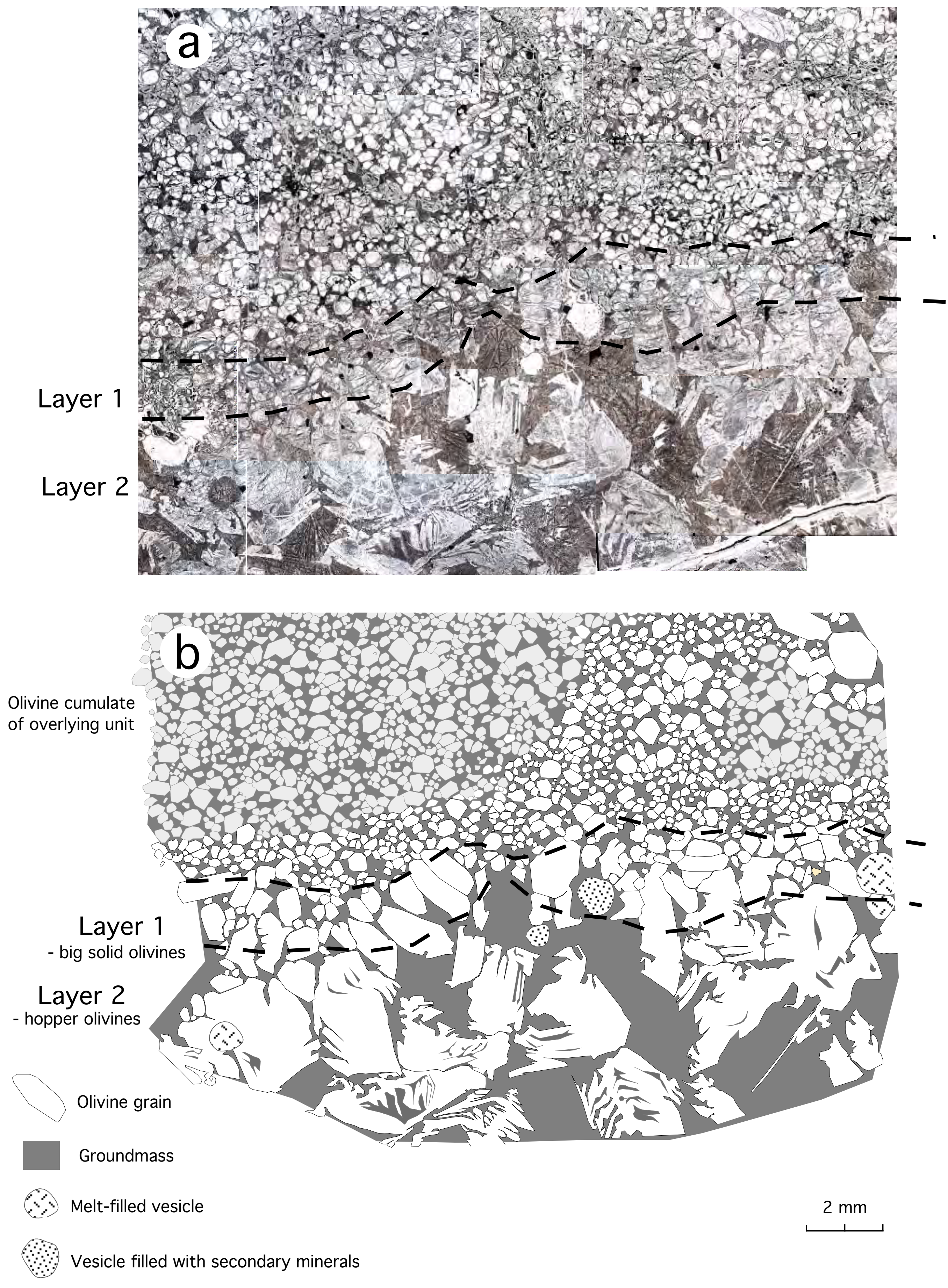

N
Komatiite
Komatiitic basalt
Interflow sedimentary rocks
Komatiitic basalt sills, peperites, and intrusive breccias
Rhyodacitic volcaniclastics
XXXXX Olivine spinifex
Olivine cumulate
Pyroxene (String Beef) Spinifex
Pepperitic (Egg-Shell) Texture
Fig. 3
Fault
Contact between member
0 5 10
Meters

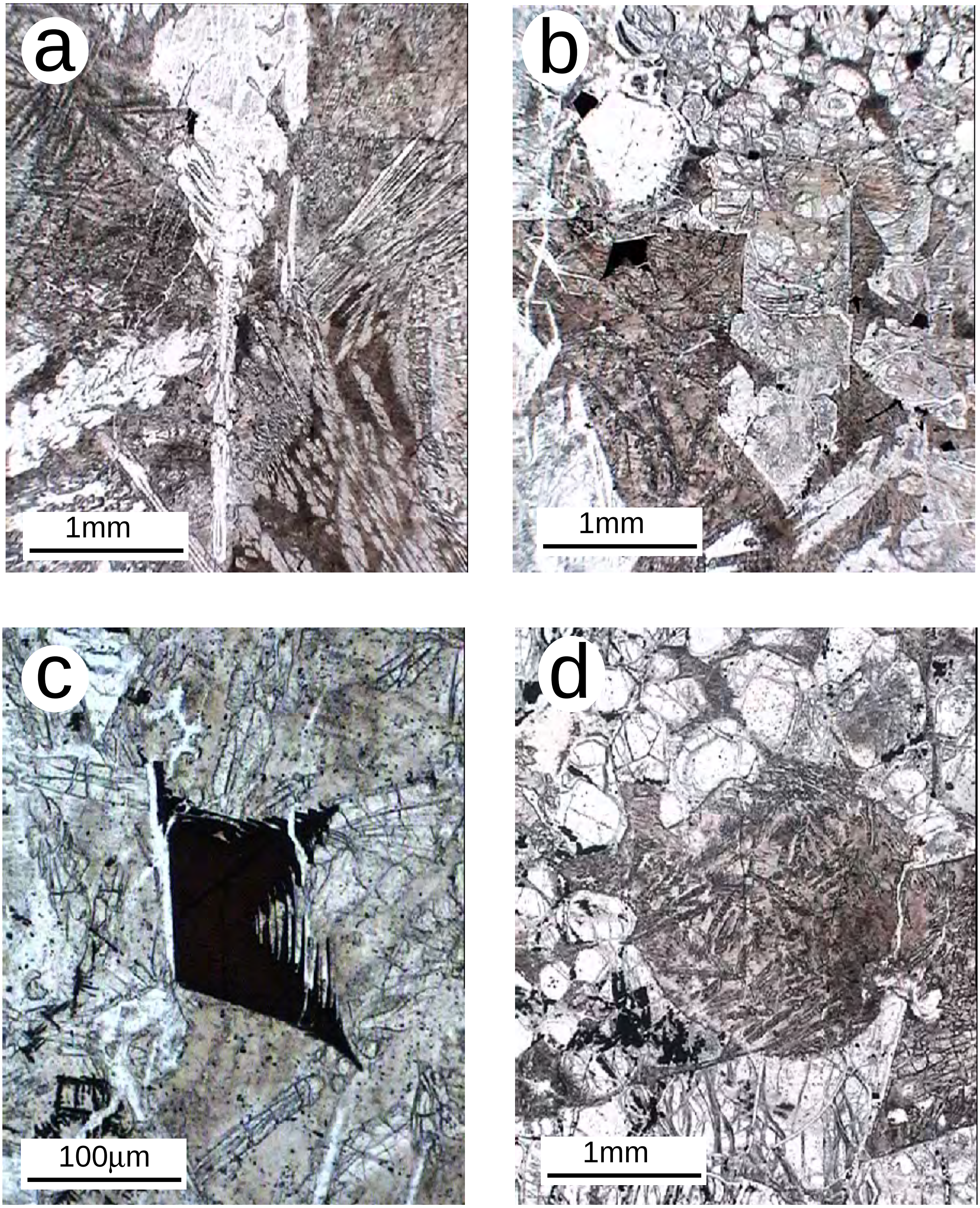


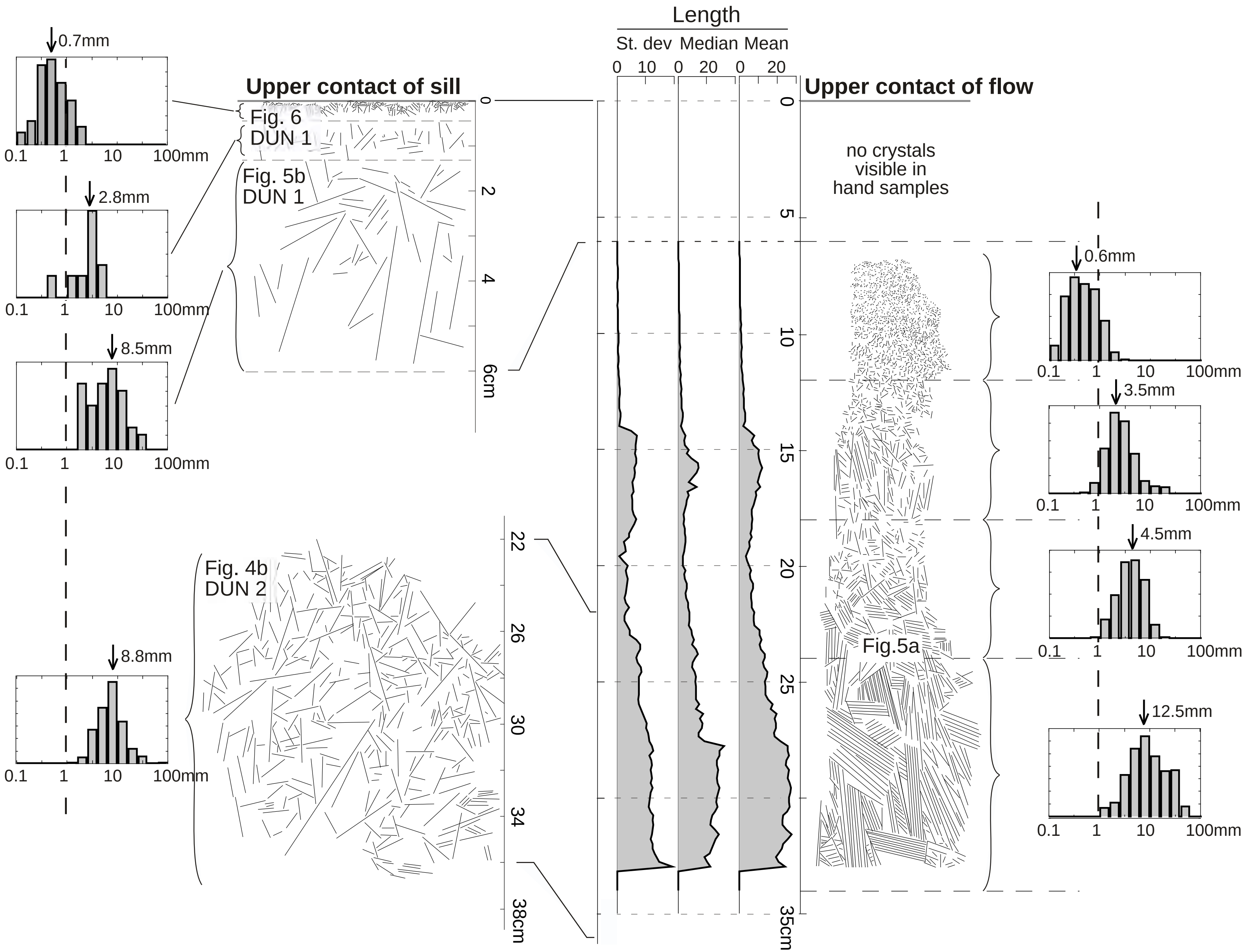
Western Dundonald Beach
N
Top of sill
DUN10
DUN1
DUN2
DUN3
DUN4
DUN5
DUN7
DUN6
DUN8
DUN9
0
1m
Random olivine spinifex
Platy olivine spinifex
Coarse dendrite spinifex
B1 zone
Olivine cumulate
Graphitic sediment
Fine-grained komatiite
Fine-grained komatiitic basalt
Oriented pyroxene spinifex
Faults
Samples


a
Flowtop
A1 zone
A2 zone
A3 zone
B1 zone
B2 zone
0.5-5 m
1-10 m
Upper chilled margin
Random olivine spinifex
Platy olivine spinifex
Horizontal skeletal olivines
Olivine cumulate
b
Olivine cumulate of overlying unit (DUN10)
Contact zone: fine hopper olivine crystals (DUN1)
Random spinifex texture (DUN2)
Plate spinifex texture (DUN 3)
Coarse dendritic spinifex texture (DUN4, 5,7)
B1 layer (DUN 5)
Olivine cumulate (DUN 6,8,9)
1-2 m
3 m
contact
2cm
1cm
2cm

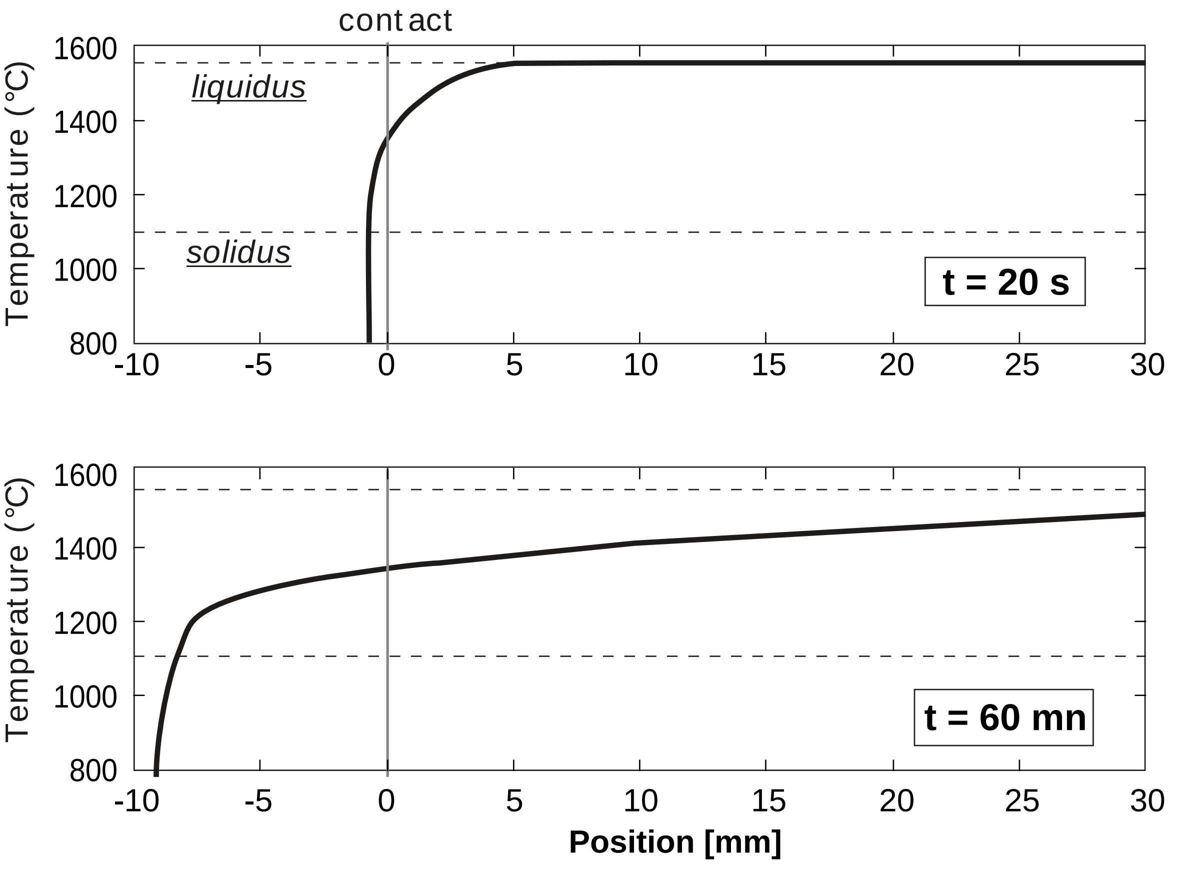

a
Fig. 6
e
p
Fig. 7a
1cm
contact
b
2cm
c
2cm


a
Layer 1
Layer 2
b
Olivine cumulate of overlying unit
Layer 1
- big solid olivines
Layer 2
- hopper olivines
Olivine grain
Groundmass
Melt-filled vesicle
Vesicle filled with secondary minerals
2 mm


a
1mm
b
1mm
c
100μm
d
1mm



Length
St. dev
Median
Mean
Upper contact of sill
Upper contact of flow
Fig. 6
DUN 1
Fig. 5b
DUN 1
Fig. 4b
DUN 2
Fig.5a
no crystals visible in hand samples
0.7mm
2.8mm
8.5mm
8.8mm
0.6mm
3.5mm
4.5mm
12.5mm
0.1
1
10
100mm
6cm
38cm
35cm



contact
1600
1400
1200
1000
800
Temperature (°C)
liquidus
solidus
t = 20 s
-10
-5
0
5
10
15
20
25
30
t = 60 mn
Position [mm]